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Modeling Pulsars in dense star clusters

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Abstract. Over a hundred millisecond radio pulsars (MSPs) have been observed in globular clusters (GCs), motivating theoretical studies of the formation and evolution of these sources through stellar evolution coupled to stellar dynamics. Here we study MSPs in GCs using realistic N-body simulations with our Cluster Monte Carlo code. We show that neutron stars (NSs) formed in electron-capture supernovae can be spun up through mass transfer to form MSPs. Both NS formation and spin-up through accretion are greatly enhanced through dynamical interaction processes. We find that our models for average GCs at the present day with masses $\approx 2 \times 10^5\, M_\odot$ can produce up to $10 - 20$ MSPs, while a very massive GC model with mass $\approx 10^6\, M_\odot$ can produce close to 100. We show that the number of MSPs is anti-correlated with the total number of stellar-mass black holes (BHs) retained in the host cluster. As a result, the number of MSPs in a GC could be used to place constraints on its BH population. Some intrinsic properties of MSP systems in our models (such as the magnetic fields and spin periods) are in good overall agreement with observations.

Keywords. globular clusters: general — stars: neutron — pulsars: general — stars: kinematics and dynamics — methods: numerical

1. Introduction

Globular clusters (GCs) are known to be highly efficient at producing millisecond pulsars (MSPs). Since the discovery of radio MSPs in GCs in the 1980s (Lyne *et al.* 1987), multiple pulsar surveys have found 155 pulsars in 29 GCs† (for reviews, see Camilo & Rasio 2005; Ransom 2008), including 38 in Terzan 5 and 25 in 47 Tuc. GCs also contain many low-mass X-ray binaries (LMXBs; Clark 1975) with neutron star (NS) accretors. The low surface magnetic fields ($\sim 10^7 - 10^9$ G) and short spin periods ($\lesssim 30$ ms) of MSPs suggest that they are "recycled" pulsars (Alpar *et al.* 1982) with LMXBs as their likely progenitors. While the physics is far from being understood in detail, it is plausible that mass transfer onto old, slowly spinning NSs can "bury" their magnetic fields while at the same time spinning them up (e.g., Bhattacharya & van den Heuvel 1991; Rappaport *et al.* 1995; Kiel *et al.* 2008; Tauris *et al.* 2012, and references therein).

The large numbers of MSPs and NS LMXBs suggest that a typical Galactic GC on average contains at least a few hundred NSs (e.g., Ivanova *et al.* 2008). However, observations show that the majority of NSs in the Galactic field are born with velocities $\gtrsim 200\, \mathrm{km\, s^{-1}}$ due to natal kicks associated with asymmetries in core collapse supernovae (CCSNe; see, e.g., Hobbs *et al.* 2005). Thus most of the CCSN NSs are ejected from

† GC pulsar catalog: http://www.naic.edu/ pfreire/GCpsr.html

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GCs at birth. Studies suggested that electron-capture supernovae (ECSNe) can solve the retention problem (Podsiadlowski *et al.* 2004; Ivanova *et al.* 2008) by producing NSs with an order of magnitude smaller natal kicks in explosions of much lower energy (Podsiadlowski *et al.* 2004).

The high stellar densities in GC cores lead to frequent dynamical encounters and high formation rates of NSs, MSPs and LMXBs (Clark 1975; Hut *et al.* 1992; Pooley *et al.* 2003; Hui *et al.* 2010; Bahramian *et al.* 2013). In clusters with larger encounter rates, NSs undergo more dynamical interactions, resulting in more NSs in binaries and binaries with shorter orbital periods. Additionally, BHs could have a strong influence on the formation of NS binaries by altering the evolution of their host GCs.

2. Neutron Star Formation and Evolution

In this study, we have updated the prescriptions for the evolution of NSs from `SSE` and `BSE` (Hurley *et al.* 2000, 2002) in our Cluster Monte Carlo code (`CMC`)†. These updates include changes to the magnetic field and spin-period evolution for single and binary NSs, and to the natal kick prescriptions for NSs formed in ECSNe (Kiel *et al.* 2008; Kiel & Hurley 2009). We perform full, self-consistent simulations for the cluster dynamics.

In our models, NSs formed in ECSNe are the dominant type of retained NSs in the cluster, and in all NS-LMXBs and MSPs. We assume that an ECSN happens whenever an ONeMg WD reaches a critical mass $M = 1.38\,M_{\odot}$. We give small natal kicks to ECSN NSs, drawn from a Maxwellian distribution with a dispersion $\sigma_{ECSN} = 20\,\mathrm{km\,s^{-1}}$ (Kiel *et al.* 2008).

To model the evolution of NS magnetic field and spin period, we follow the prescriptions described in Hurley *et al.* (2002) and Kiel *et al.* (2008). As outlined in Kiel *et al.* (2008), we assume that the dominant spin-period evolution mechanism for single NSs is dipole radiation, and NSs are treated as solid spheres. Additionally, magnetic fields of single NSs are assumed to decay exponentially on a timescale of 3 Gyr (Kiel *et al.* 2008). For NSs in binaries, binary evolution is also taken into account. The evolution of NSs in detached binaries is the same as for single NSs. On the other hand, during mass-transfer episodes, the magnetic fields and spin periods of NSs can change significantly on a short timescale. Wind mass loss, tidal evolution, magnetic braking and supernova kicks have only small effects on the magnetic field and spin period evolution. Only stable mass transfer in a binary system can spin up NSs to MSPs in our models; we ignore the possibility of mass accretion by NSs during common-envelope phases (Hurley *et al.* 2002).

We plot all the pulsars in our models on top of all observed pulsars in the GC pulsar catalog in Figure 1. There are both MSPs ($P \lesssim 30\,\mathrm{ms}$) and young pulsars in our models, as are observed in GCs. Most of the pulsars observed in Galactic GCs are MSPs, as expected since MSPs have long lifetimes and can exist in GCs for many Gyr. In contrast, young pulsars have relatively short lifetimes, and those formed at early times in GCs are no longer there. However, through dynamical interactions such as collisions between a MS star and a WD, young pulsars can be formed at the present time in old GCs.

3. Black Hole-Millisecond Pulsar Anti-correlation

We find a clear anti-correlation between the number of retained BHs and the number of MSPs in our models (Fig. 2). This anti-correlation was anticipated, based on our understanding of BH populations in GCs. BHs dynamically influence the NSs including the MSPs in the clusters. As long as many are present, BHs dominate the cluster cores because of mass segregation and they prevent the NSs from concentrating in

† For recent review of `CMC`, see, e.g., Pattabiraman *et al.* (2013); Chatterjee *et al.* (2013a); Rodriguez *et al.* (2018)

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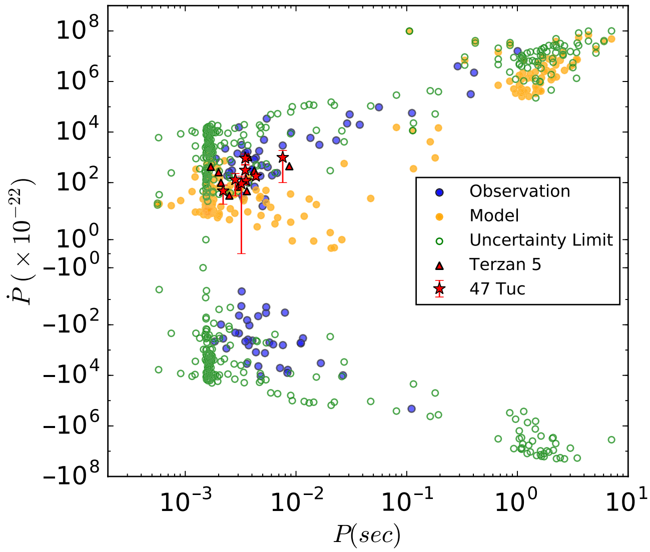

Figure 1. Spin periods and spin period derivatives of pulsars. The blue dots show all observed GC pulsars (except the 5 newly detected pulsars in Omega Centauri (Dai *et al.* 2020)). The red stars and triangles show the pulsars in 47 Tuc with derived intrinsic spin period derivatives and in Terzan 5 with inferred magnetic fields (Freire *et al.* 2017; Prager *et al.* 2017). The orange dots show the intrinsic $\dot{P}$ values for our model pulsars; the green dots show the corresponding apparent $\dot{P}$ values taking into account acceleration in the cluster potential. This is a reproduction of Figure 6 from Ye *et al.* 2019.

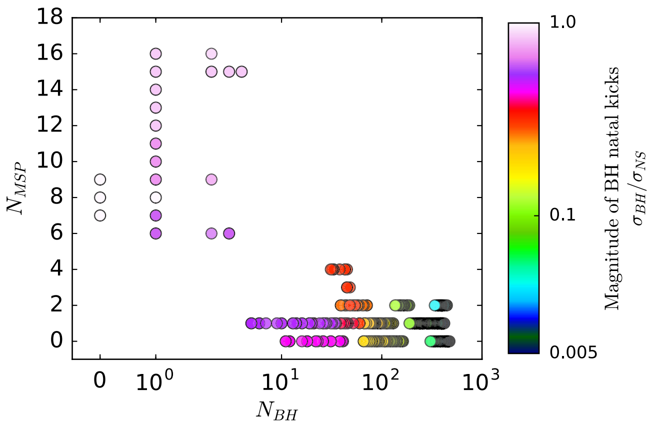

Figure 2. Number of MSPs vs number of BHs between 9 and 12 Gyr in models. Models with different BH natal kicks are shown with different colors. There is a clear anti-correlation between these two numbers. This is a reproduction of Figure 4 from Ye *et al.* 2019.

the high-density central region. Furthermore, GCs with more retained BHs have lower core densities due to the heating of the cores from BH interactions (Mackey *et al.* 2008; Morscher *et al.* 2015; Chatterjee *et al.* 2017; Arca Sedda *et al.* 2018; Kremer *et al.* 2018; Fragione *et al.* 2018). This also affects the number of encounters the NSs can have during the cluster evolution. NSs located closer to the centers go through more dynamical interactions. Therefore NSs in models with few BHs are more likely to acquire companions and accrete mass, and thus, a larger chance to become MSPs at late times.

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4. Discussion

As this is our very first attempt at studying the formation of MSPs within our CMC code, for simplicity, we did not explore the various uncertainties associated with the treatment of binary evolution in BSE, and instead we focused on general trends (for example the anti-correlation between MSPs and BHs). We do get good overall agreement with observations, in the sense that our models produce reasonable numbers of all observed type of systems (single vs binary MSPs, very low-mass companions vs MS star companions, slow vs fast pulsars; Ye *et al.* 2019), suggesting that our current very simple treatment for the evolution of magnetic fields and spin periods of NSs in CMC is sufficient for this first attempt at a detailed comparison. More closely matching observations (e.g., ratio between different types of pulsar binaries) would require a more sophisticated treatment of the binary evolution physics, which will be considered in future works.

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